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W Boson Cross Section and Decay Properties at the Tevatron

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We present the first measurements of $\sigma(p\bar{p} \to W \to \ell\nu)$ and $\sigma(p\bar{p} \to Z \to \ell\ell)$ at $\sqrt{s} = 1.96$ TeV, along with new measurements of W angular-decay distributions in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV.

1. W/Z production cross sections

W and Z boson production cross-section measurements in $p\bar{p}$ collisions are a test of the consistency of Standard-Model couplings, constrain proton parton distribution functions, and provide information on higher-order QCD corrections. They also test the mettle of an experiment, as the measurements require good understanding of detection efficiencies, backgrounds, and luminosity. If experimental uncertainties are small, and the cross sections can be well-estimated from theory, the boson production rates can be interpreted as a measure of luminosity, and can also be used to normalize measurements of other production cross sections. Finally, W and Z bosons provide a path to the physics of Run II at the Tevatron, where many signatures of top-quark and Higgs-boson production can include these bosons.

At the Tevatron, protons and antiprotons collide at a center-of-mass energy of 1.96 TeV. A W boson appears in the detector as a high-momentum lepton and large missing energy due to the undetected neutrino. As the z component of p^{ν} is unmeasured, all quantites are measured in the transverse plane. A Z boson appears as two high-momentum opposite-signed leptons with an invariant mass around 90 GeV. The cross section can be expressed as

$$\sigma \cdot B = \frac{N_{obs} - N_{bg}}{A\epsilon \int \mathcal{L}dt}, \tag{1}$$

where N_{obs} is the number of observed boson events, N_{bg} is the estimated number of background events, A is the kinematic and geometric acceptance, ϵ is the total efficiency, and $\int \mathcal{L}dt$ is the integrated luminosity.

The lepton plus missing transverse-energy sample can be accounted for by $W \to \ell\nu$, $Z \to \ell\ell$, $W \to \tau\nu$, QCD jets (fake leptons), and (for muons) cosmic rays, as illustrated in Figure 1. CDF measures the W cross section in the electron and muon decay channels, and D0 does so in the electron channel. (CDF also looks at mono-jet events with large missing energy, and sees an enhancement in the number of jets with one and three charged tracks, evidence for $W \to \tau\nu$ decays.) The inputs and results for the cross-section measurements are given in Table 1. The measurements are systematics-limited, with the overall uncertainty typically dominated by the uncertainty in the integrated-luminosity measurement. The quoted uncertainty on the luminosity should be considered an upper limit.

The dilepton samples are quite clean and allow for easy identification of the Z resonance, as seen in Figure 2. D0 measures $\sigma \cdot B(Z \to ee)$, with the result shown in Table 2. From this and the W cross-section measurement, D0 calculates the ratio of cross sections $R_\ell = \sigma^W/\sigma^Z$, also given in Table 2; CDF measures the same ratio in the muon channel. This ratio can be expressed as

$$R_\ell = \frac{\sigma(p\bar{p} \to W)}{\sigma(p\bar{p} \to Z)} \frac{\Gamma(W \to \ell\nu)}{\Gamma(Z \to \ell\ell)} \frac{\Gamma(Z)}{\Gamma(W)}. \tag{2}$$

Taking the total cross-section values and $\Gamma(W \to \ell\nu)$ from theory, and the Z branching fraction from measurements at the Z pole, $\Gamma(W)$ can be extracted. The D0 R measurement gives $\Gamma(W) = 2.26 \pm 0.18_{\mathrm{stat}} \pm 0.29_{\mathrm{sys}} \pm 0.04_{\mathrm{external}}$ GeV, and the CDF measurement of R implies $\Gamma(W) = 1.67 \pm 0.24^{+0.14}_{-0.13} \pm 0.01$ GeV. The current world average

Table 1
Measurement of the W cross section at CDF and D0.

	CDF $W \to e\nu$	CDF $W \to \mu\nu$	D0 $W \to e\nu$
N_{obs}	5547	4561	9205
N_{bg}	409 ± 85	569 ± 63	5782 ± 357
A (%)	23.4 ± 0.9	14.2 ± 0.4	19.6 ± 0.9
ϵ (%)	81.1 ± 1.8	63.2 ± 3.8	86.5 ± 3.6
$\int \mathcal{L}dt$ (pb^{-1})	10.4 ± 1.0	16.5 ± 1.6	7.5 ± 0.8
$\sigma \cdot B$ (nb)	$2.60 \pm 0.03_{\rm stat} \pm 0.13_{\rm sys} \pm 0.26_{\rm lum}$	$2.70 \pm 0.04_{\rm stat} \pm 0.19_{\rm sys} \pm 0.27_{\rm lum}$	$2.67 \pm 0.06_{\rm stat} \pm 0.33_{\rm sys} \pm 0.27_{\rm lum}$

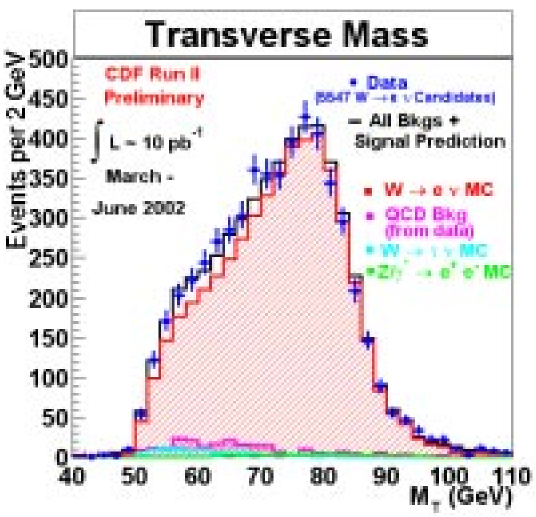

Figure 1. Transverse-mass distribution for the CDF electron plus missing energy sample.

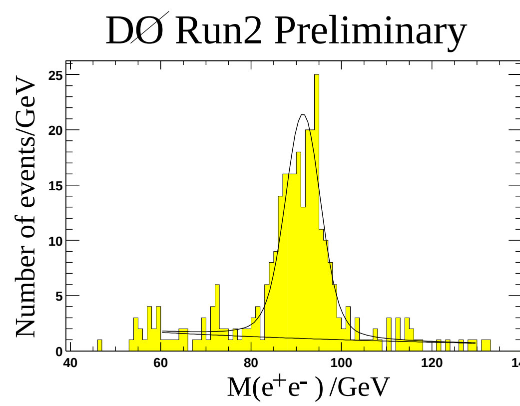

Figure 2. Invariant-mass distribution for the D0 dielectron sample.

is $\Gamma(W) = 2.114 \pm 0.043$ GeV [1].

All of the CDF and D0 cross-section measurements are summarized in Table 2. For comparison, the best measurements of these quantities in Run I data are $\sigma^W = 2.49 \pm 0.12$ nb [2], $\sigma^Z = 249 \pm 11$ pb [3], and $R = 10.90 \pm 0.43$ [4]. The Run II measurements have not reached that level of precision, but they should with additional data. In addition, the W and Z production cross sections at the Run II energy of 1.96 TeV are expected to be about 10% larger than those at the Run I energy of 1.8 TeV; theory predicts values of $\sigma^W = 2.73$ (2.50) nb and $\sigma^Z = 250$ (230) pb at $\sqrt{s} = 1.96$ (1.8) TeV [5]. The measured values are consistent with this predicted rise, as illustrated in Figure 3.

2. W-decay angular distributions

Understanding QCD effects in W production helps reduce uncertainties in M_W and other electroweak measurements. Without QCD, when the W has no transverse momentum (p_T^W), the differential cross section for the charged lepton in the W decay is $\propto (1 + q_\ell \cos\theta)^2$, as predicted by the $V - A$ interaction. But in NLO QCD, the differential cross section in the Collins-Soper rest frame is given as

$$\frac{d^4\sigma}{dp_T^W\, dy d(\cos\theta) d\phi} \quad \propto \quad 1 + \cos^2\theta +$$

Table 2
Summary of cross-section measurements; uncertainties are from statistics, systematics, and luminosity normalization.

Quantity	Source	Value
σ_e^W (nb)	CDF	$2.60 \pm 0.03 \pm 0.13 \pm 0.26$
σ_μ^W (nb)	CDF	$2.70 \pm 0.04 \pm 0.19 \pm 0.27$
σ_e^W (nb)	D0	$2.67 \pm 0.06 \pm 0.33 \pm 0.27$
σ_e^Z (pb)	D0	$266 \pm 20 \pm 20 \pm 27$
R_e	D0	$10.0 \pm 0.8 \pm 1.3$
R_μ	CDF	$13.7 \pm 1.9^{+1.1}_{-1.2}$

$$\begin{aligned} &A_0(1-3\cos^2\theta)/2 + \\ &A_1 \sin 2\theta \cos\phi + \\ &A_2(\sin^2\theta\cos 2\phi)/2 + \\ &A_3 \sin\theta\cos\phi + \\ &A_4 q_\ell \cos\theta + \\ &A_5 \sin^2\theta \cos 2\phi + \\ &A_6 \sin 2\theta \sin\phi + \\ &A_7 \sin\theta\sin\phi, \end{aligned} \tag{3}$$

where the A_i depend on p_T^W and the boson rapidity; the latter is typically integrated out. (The A_1, A_5, A_6 and A_7 terms can be safely neglected.) Thus, angular distributions when $p_T^W \neq 0$ probe the values of the A_i, which can then be compared to predictions from NLO QCD. The D0 experiment has made a measurement of A_0 in Run I data[6], and CDF now has measurements of A_0, A_2 and A_3 from Run I data.

The θ distribution of the decay leptons is obtained by integrating Equation 3 over ϕ:

$$\frac{d\sigma}{d(\cos\theta)} \propto 1 + q_\ell \alpha_1 \cos\theta + \alpha_2 \cos^2\theta, \tag{4}$$

with $\alpha_1 = A_4/(2+A_0)$, $\alpha_2 = (2-3A_0)/(2+A_0)$. There is no sensitivity to α_1 due to the unknown p_z^ν, but there is sensitivity to α_2 through the shape of the W transverse-mass spectrum, which changes with p_T^W. The Run I CDF W sample is separated into four bins of p_T^W, and in each one a maximum-likelihood fit to the M_T spectrum is performed to extract α_2, accounting for background contamination and detector acceptance. The results are shown in Figure 4, along with the

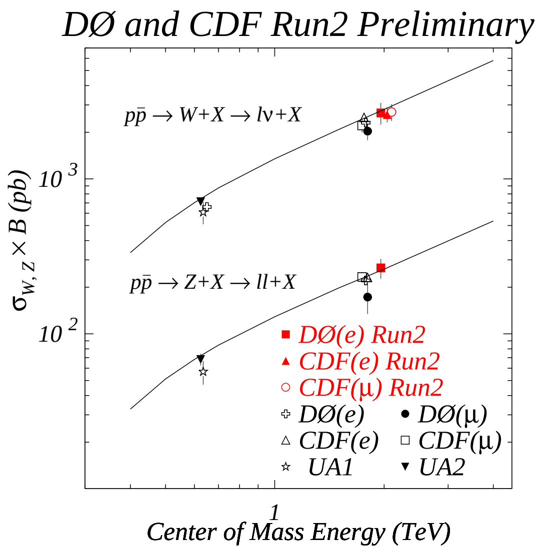

Figure 3. W and Z cross-section measurements at different center-of-mass energies, with theoretical prediction.

earlier D0 results and the prediction from QCD. There is good agreement among all three; the decrease in α_2 with p_T^W indicates increasing longitudinal polarization, as is expected. The CDF measurement is statistics-limited, with systematic uncertainties dominated by uncertainty in M_W, p_z^W, and the model of the W recoil.

Similarly, one can integrate over θ in Equation 3 to obtain an expression that depends on ϕ. Measuring the ϕ distribution of the lepton from W decay gives information on the A_2 and A_3 coefficients. Again, events from the Run I CDF W sample are separated into four bins of p_T^W; the events are required to have at least one hadronic jet to ensure that $p_T^W > 0$. A maximum-likelihood fit to the ϕ distribution is performed to extract A_2 and A_3. The results are shown in Figure 5, along with the prediction from QCD. As before, the experimental results are in agreement with the theory prediction. The A_2 measurement is systematics-limited, with the dominant uncertainties coming from the knowledge of A_0 and A_4, and the renormalization and factor-

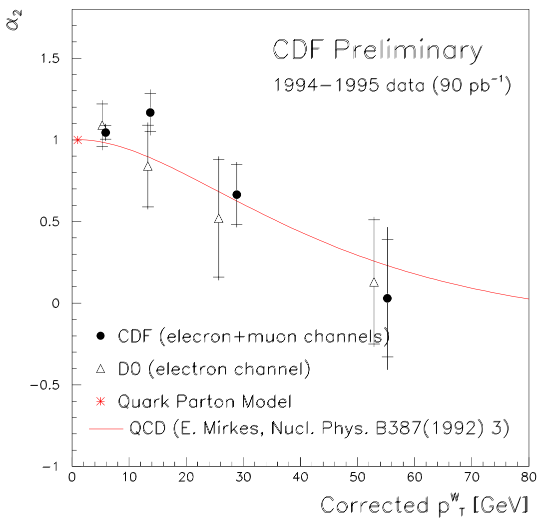

Figure 4. CDF measurement of α_2 as a function of p_T^W, along with earlier D0 measurement and QCD prediction.

ization scale. By contrast, the A_3 measurement is statistics-limited.

3. Summary

Run I at the Tevatron has produced a trove of knowledge about the W and Z bosons, as evidenced by the new CDF measurement of the W angular-decay distributions. These sophisticated analyses will be completed soon. The CDF and D0 collaborations are now turning their attention to the Run II data, and their W and Z-based analyses are underway. Both experiments have established techniques to identify the bosons with high efficiency. They have a good understanding of the acceptances and efficiencies of their detector, and this understanding will improve as more data are collected. The W cross-section measurements are consistent with the theory predictions and expectations from earlier measurements, and are already systematics-limited. Measurements of the Z cross section and R tend to be statistics-limited, but that too will change as the datasets grow. This work provides a solid foundation for the studies of high-p_T physics that are among the goals of Run II.

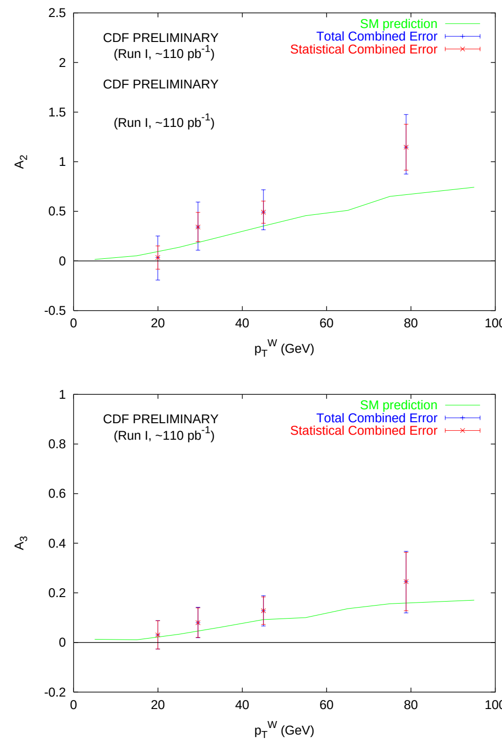

Figure 5. CDF measurement of A_2 (top) and A_3 (bottom) as a function of p_T^W, along with the QCD prediction.

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